FAA Rotorcraft Review Meeting

Applying Damage Tolerance to Propeller Systems

(NASA JSC Project 1)

Royce Forman, David Shindo, Scott Forth (NASA JSC)

William J, Hughes Technical Center
February 13-15, 2007

Program Objectives and Participants

Objective:

Evaluate design impact of implementing DTA methodology on aircraft propeller systems

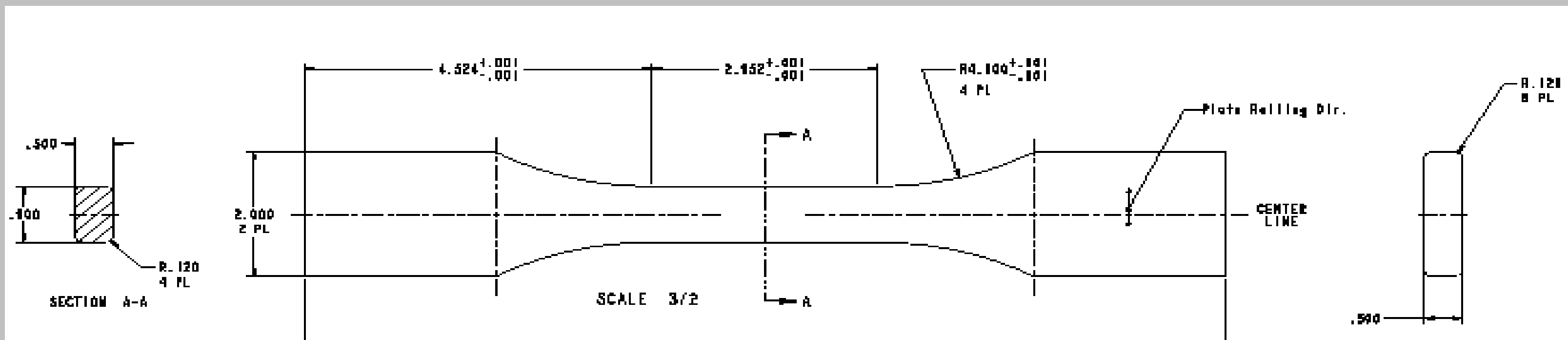
Participants:

NASA JSC - Machine and test specimens

Hamilton Sundstrand (HS) – Shot peen specimens, measure residual stresses, laser notch specimens, perform crack growth predictions with NASGRO and compare analysis with test results, write final report

SANDIA – Examine reliability of conventional NDI methods and promising new NDI techniques for their potential in being applicable to DTA of aircraft propellers

Primary Laboratory Specimen



- Surface Crack Specimens
  - 7075-T7351 Al & D6AC Steel (35 HRc)
  - 8 Unpeened (each alloy)
  - 26 Shot-peened (each alloy)
  - Constant Load Amplitude + Threshold Testing
  - Stress Ratios of 0.1 & 0.7

Material Characterization Testing

<u>Specimens Planned for both alloys:</u>

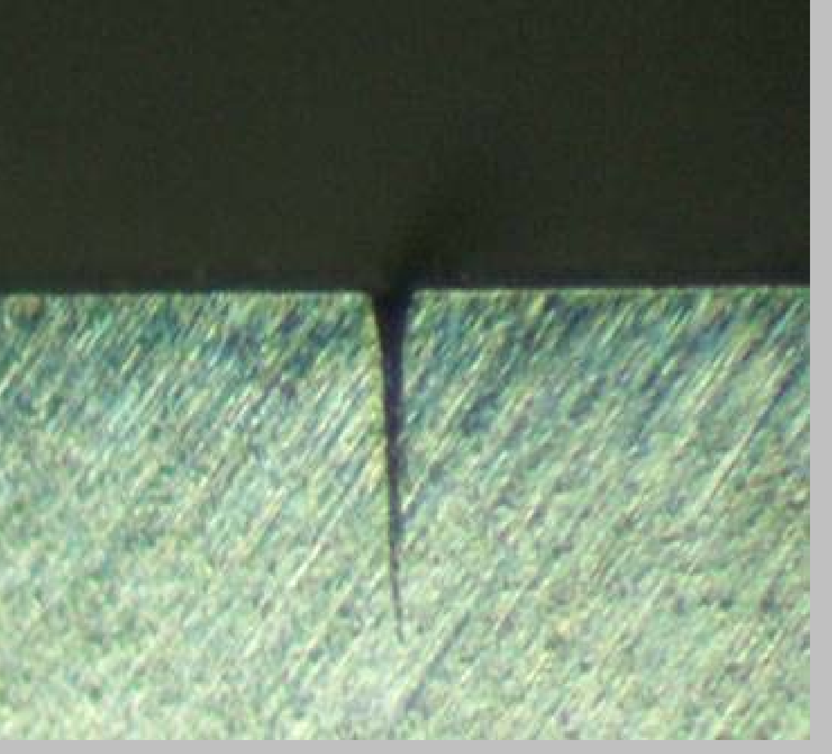
M(T), C(T) & ESE(T) – 8 of each type (24 total)

<u>Limitations in D6AC testing:</u>

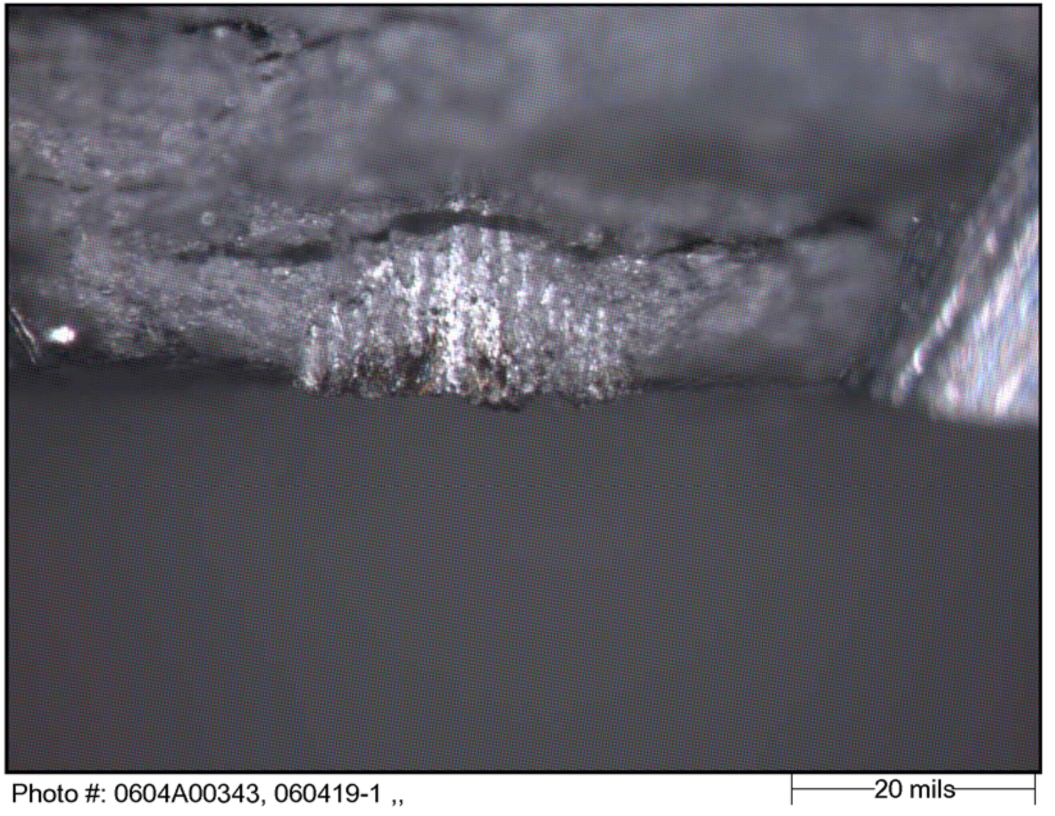
- **Many of the 24 specimens were machined before discovery that the stock material had not been heat treated.**
- **Thus, all C(T) and some ESE(T) specimens cracked at the notches during subsequent heat treatment.**
- **As a result, more ESE(T) specimens will be machined from several M(T) specimen blanks and more of C(T) type machined from tested M(T) specimens.**
- **No more stock D6AC material remains due to the large amount required to fabricate 44 dogbone specimens.**

Machining of small surface “crack like” notches into primary test specimens

- **Laser etching used to put in surface cracks**
  - Photo is 0.012 inches in depth
  - Semi-circular surface crack
- **Photos and surface crack information provided by Aaron Nardi, United Technologies Research Center; Steve Smith, Hamilton Sundstrand**



Making the 12.5 mil deep Crack



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Comment: Sample with CCAT parameter set from April 19, 2006. Using cutting parameters of 20 khz frequency, 25 pulse width, 100 mm/s, and cleaning parameters of 80khz pulse frequency 2.5 pulse wid and 500 mm/s. 2 cutting passes then 1 cleaning pass. Incrementing down in length and up in power w sucessive passes.

Program Status

- 40 fabricated 7075 AL dogbone specimens shipped to HS on 4/7/06
- 44 fabricated D6AC specimens ready to ship to HS
- Testing of 7075 Al ESE(T) & M(T) specimens & D6AC ESE(T) specimens in progress
- Contract agreement for HS to begin work was only recently signed and , thus, full work by all participants can now proceed.

FAA Rotorcraft Review Meeting

Development and Validation of Enhanced Analysis Tools to Assess the Damage Tolerance of Rotorcraft

(NASA JSC Project 2)

Royce Forman, David Shindo, Scott Forth (NASA JSC)

William J, Hughes Technical Center
February 13-15, 2007

Four Year Project Outline

- TASK 1: Fatigue crack initiation and propagation from corrosion pits (2006-2008)
- TASK 2: Fatigue crack growth behavior of small surface cracks (2007-2009)
- TASK 3: Growth behavior of surface and through cracks undergoing applicable spectrum fatigue loading (2008-2010)
- TASK 4: Development of required fatigue crack growth properties that are lacking for certain rotorcraft metal alloys (2007-2010)

Task 1 Plans & Progress

- Develop baseline da/dN properties for the primary test alloys 7075-T7351 Al Plate and 4340 (190 UTS) Forged Steel (Essential for Tasks 1, 2 & 3):

  Progress: M(T), C(T) & ESE(T) specimens fabricated and being tested.

- Induce specific sized *corrosion pits* in dogbone type test specimens, both peened and unpeened specimens, and fatigue test in tension to determine crack initiation cycles and crack growth rates:

  Progress:

  (1) Numerous small 7075 Al test blocks were fabricated and an acceptable pitting technique has been developed with these blocks.

  (2) The 44 aluminum dogbone specimens have been machined and 44 steel specimens are now being machined. Of each set of 44 specimens - 16 are to be unpeened, 14 to be shot peened and 14 to be laser peened).

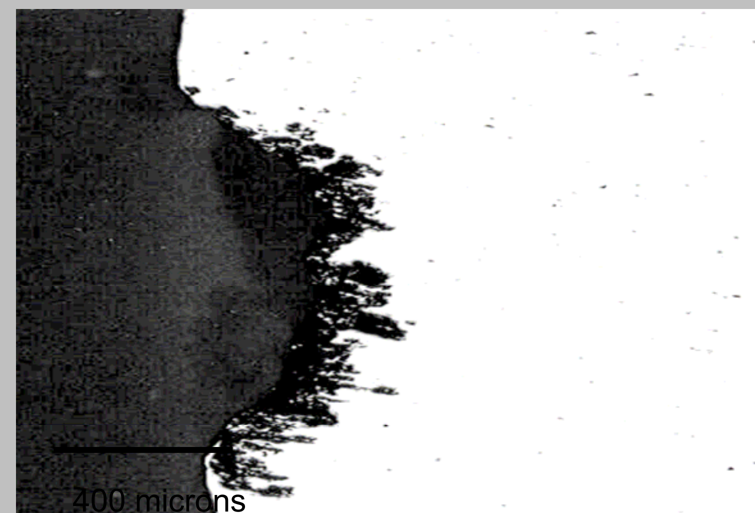
- Develop analytic methodology for crack formation and crack growth rate for cracks growing from corrosion pits, evaluate methodology using derived test data and implement methodology into NASGRO.

Fatigue Cracks from Corrosion Pits

Improved analysis will be very beneficial to NASA space programs

Recent Example - Corrosion pitting of Shuttle landing gear wheels resulted in $3M study effort:

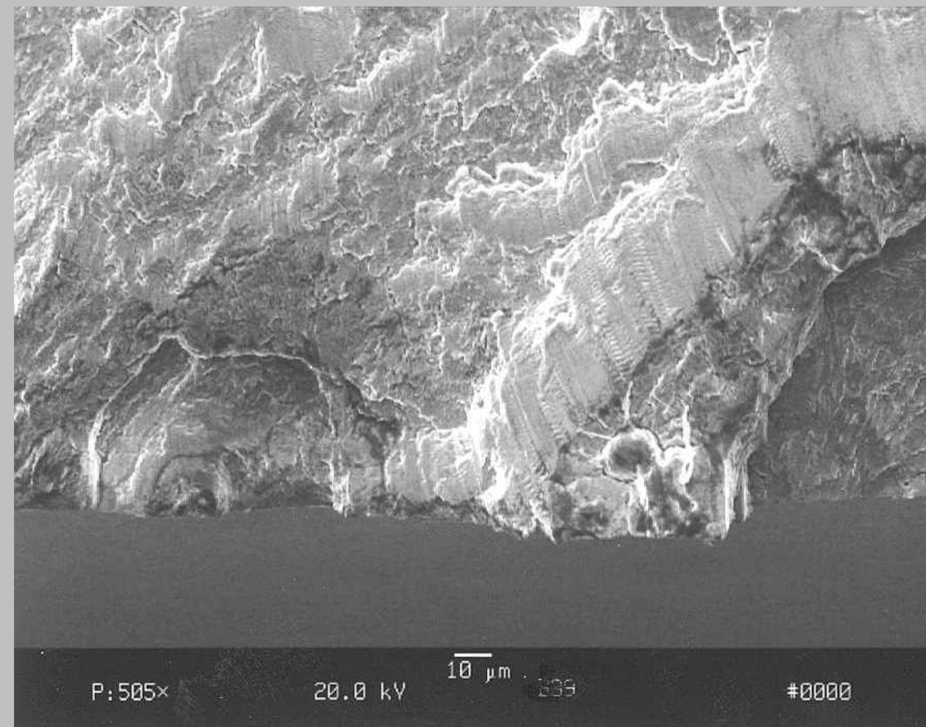
- NASGRO analysis assuming a pit as a crack resulted <1 safe landing
- Analysis was over conservative because of original conservative stress analysis and the omission of crack formation fatigue cycles.
- Wheel testing at WPAFB showed more than 12 safe landings with negligible crack growth from existing pits.



Metallographic cross section of a corrosion pit in a Shuttle MLG wheel (.o46” Dia, .010” depth)

Fatigue Cracks from Corrosion Pits
- Objectives & Plans -

- How long does it take for pits to act like cracks
- Model pit to crack transition
- Compare crack growth rates to non-corrosive cracks and compare peened with unpeened results
- Measure crack initiation and propagation with DC potential drop method
- Incorporate developments into NASGRO models

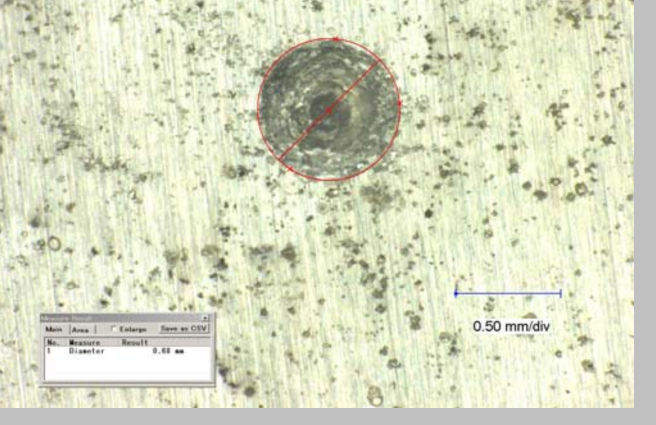


Corrosion Pitting Method Development

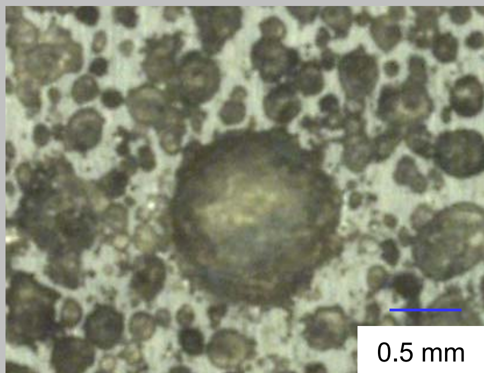
- Goals for corrosion pitting process:
  - Control of pit size
  - Repeatability
  - Realistic surface morphology
- Initial process based on methods used by Smith, et al.
- Modifications:
  - Use of drilled starter pits to control size/repeatability
  - Wax coating disbondment
    - Suitable replacement
  - Copper cathode vs. carbon cathode

Corrosion Pitting Process

1. Prepare/coat specimen surface
2. Drill starter pit/measure depth
3. Attach cell container
4. Add electrolyte (0.11N HNO_3 + 3 g/L NaCl)
5. Connect electrodes/run current
6. Remove cell/measure pit depth
7. Remove coating/measure pit



Pit Morphology & Process Optimization



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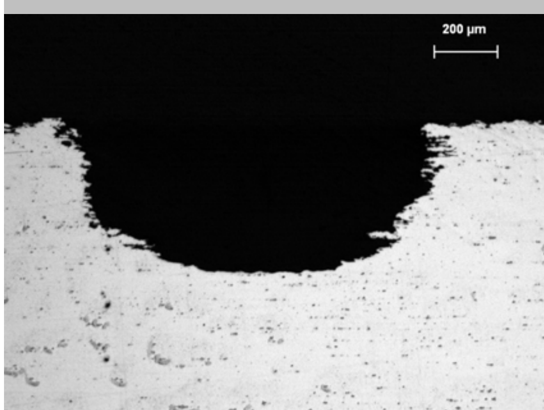

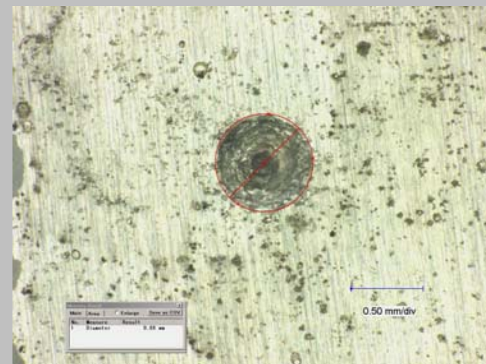

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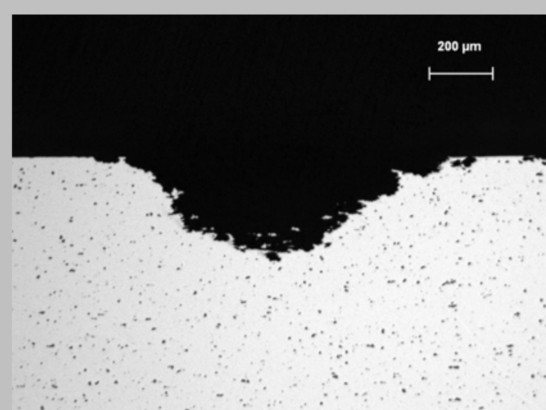

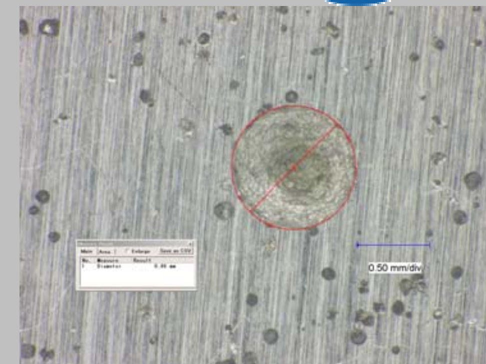

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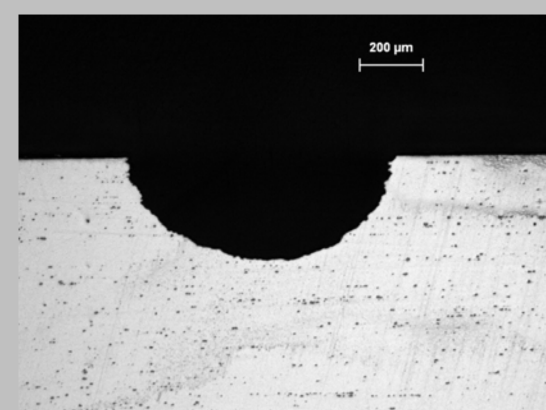
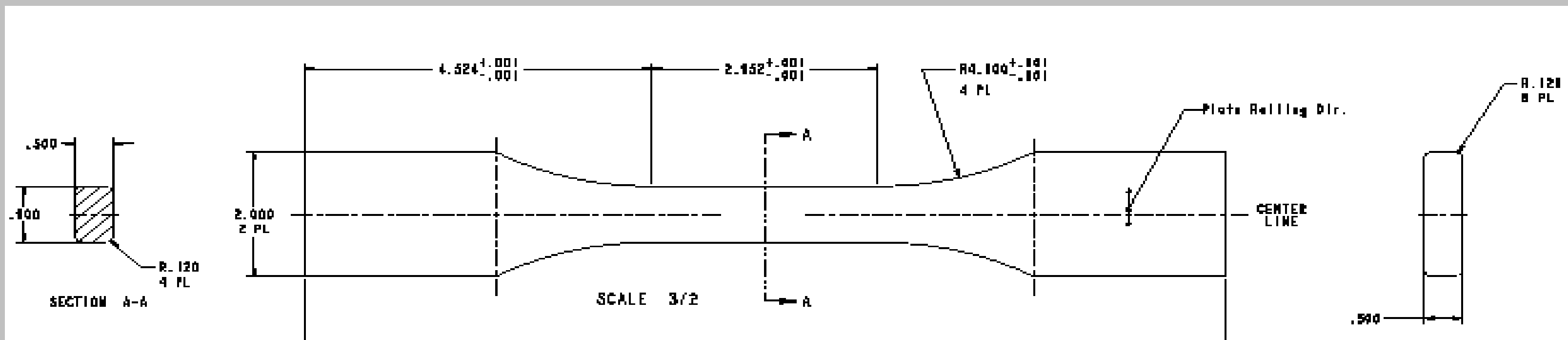
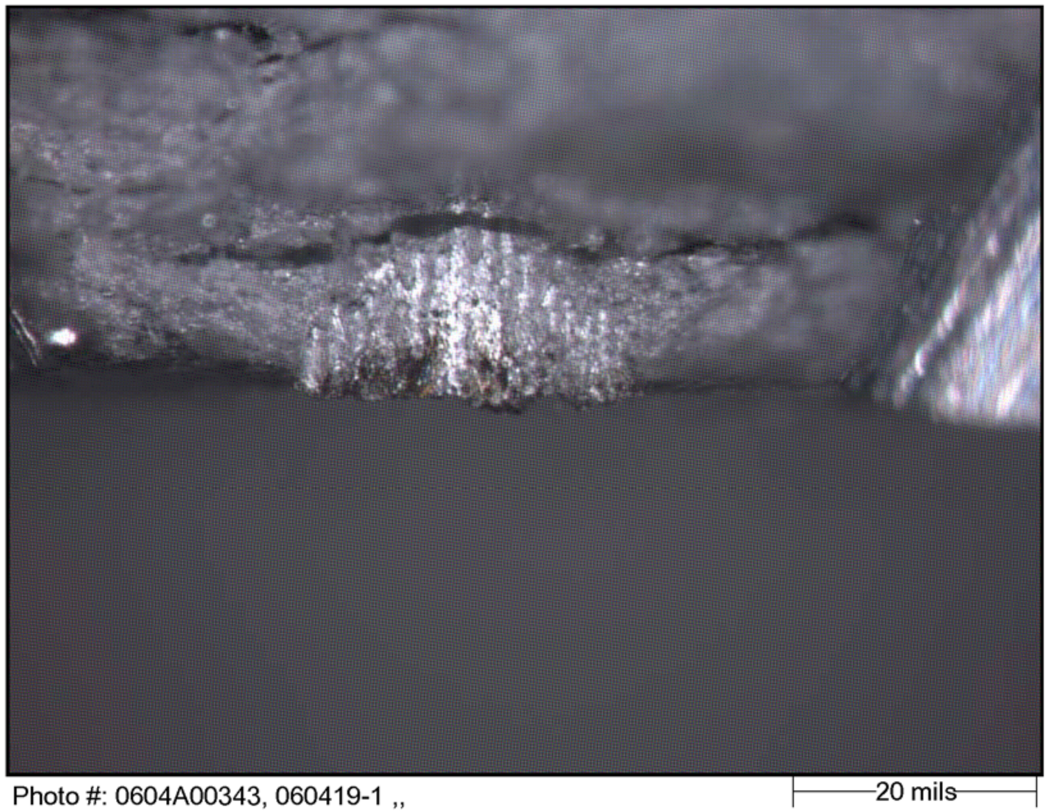


Laboratory Specimen



- Surface Crack & Corrosion Pit Specimens
  - 7075-T7351 Al & 4340 Steel
  - Unpeened
  - Shot-peened & Laser-peened
  - Constant Load Amplitude
  - Stress Ratios of 0.1 & 0.7

Laser Notching Equivalent Sized Surface Crack To Compare With Corrosion Pit



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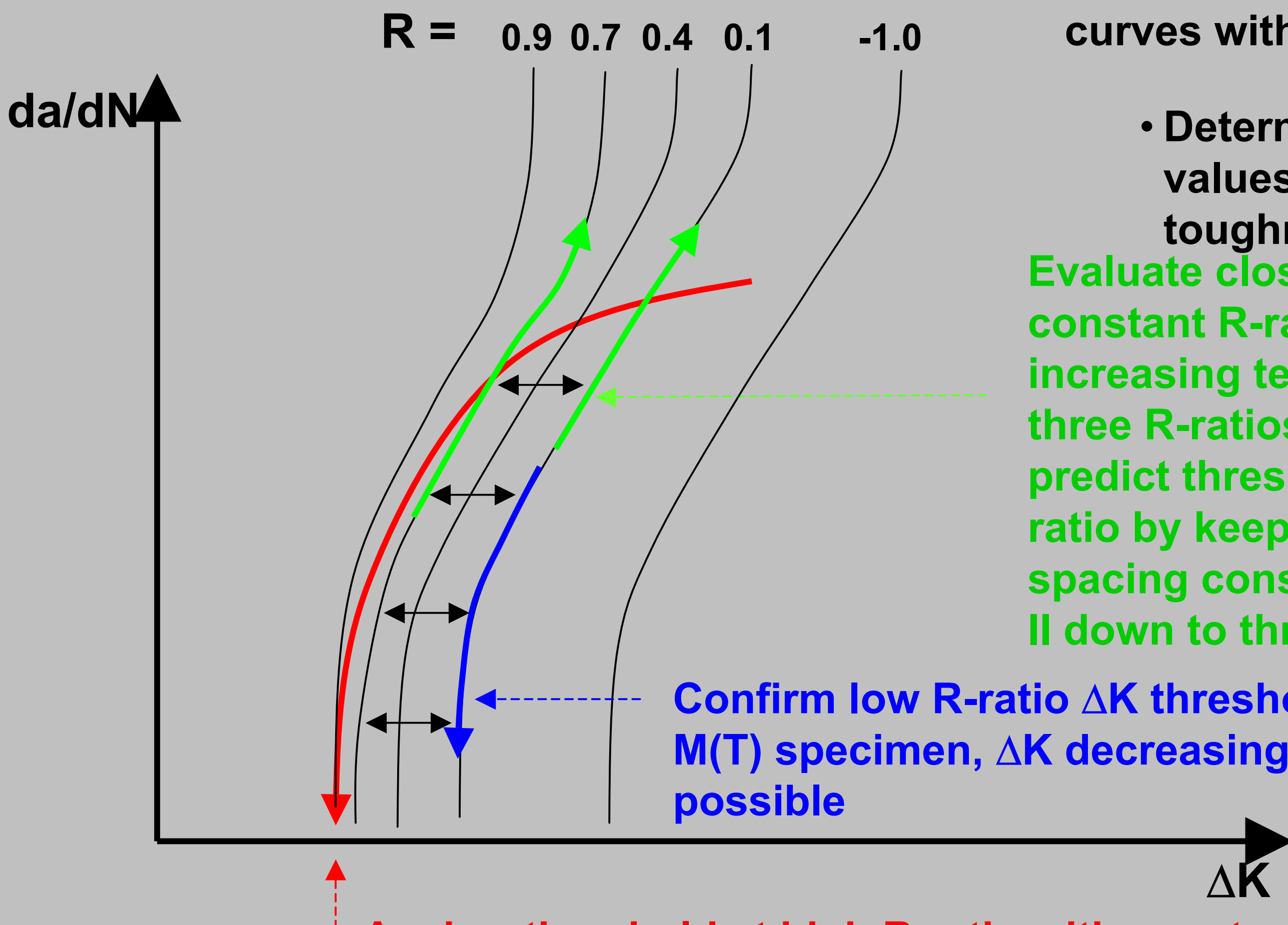
Analysis Efforts

- Residual Stress Profiles
  - X-Ray Diffraction on Surface
  - Cut Compliance for Interior
- Spectrum Load Testing
  - To be coordinated with OEMs
  - ESE(T), M(T), Surface Crack
  - Peened & un-peened specimens
- Near Threshold Testing
  - Estimate threshold w/unpeened specimens
  - Compare to traditional C(T) data
  - Estimate threshold w/peening
  - Compare measured residual stresses to affect of peening on threshold

Task 4 - Database Development

(A proposed approach)

- Determine negative R-ratio curves with M(T) specimens
- Determine instability values with E1820 toughness tests



Evaluate closure (α) with constant R-ratio, ΔK increasing tests at two or three R-ratios. Use this to predict threshold versus R-ratio by keeping curve spacing constant from stage II down to threshold.

Confirm low R-ratio ΔK thresholds with M(T) specimen, ΔK decreasing test when possible

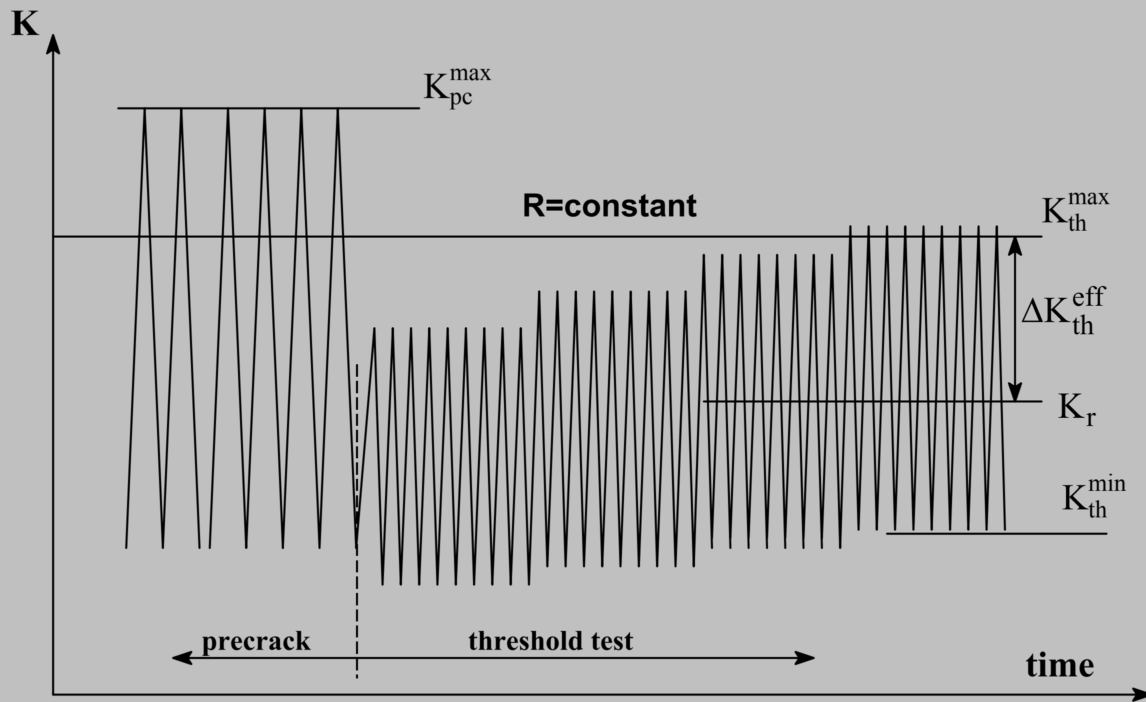
Anchor threshold at high R-ratio with constant Kmax test(s)

Concerns For Threshold Testing and Modeling

- Controversy exists on validity of threshold region data obtained when using the ASTM load shedding method.
- Assumed equal spacing of curves in threshold region is probably conservative but is it over-conservative? (i.e., can we apply damage tolerance methods on rotorcraft with this conservative assumption)
- Many spectrum loading cases, environmental conditions and crack cases (e.g. type specimen) results in “fanning-out” of curves in threshold region at low R values.

Spectrum Loading Threshold Model

(Ted Nicholas – FAA/NASA Langley Meeting July 2003)



$$K_r = \beta \left(K_{pc}^{max} + K_{th}^{min} \right)$$

$$\Delta K_{th} = \frac{\left(1 - R_{th}\right) \Delta K_{th}^{eff}}{\left(1 - \beta R_{th}\right)} + \frac{\beta \left(1 - R_{th}\right)}{\left(1 - \beta R_{th}\right)\left(1 - R_{pc}\right)} \Delta K_{pc}$$

Data Base Development – Other Complications

- M(T) specimens often have unacceptable crack tunneling, uneven crack growth, early net section yielding and requires much lower loading frequency (e.g. 20 vs 60 Hz)
- Difficult to obtain sufficient sized M(T) specimens from forgings.
- Residual stresses and complicated grain orientations causes problems in obtaining valid and consistent data, particularly in specimens machined from forged aircraft components.
- JSC requires improved assistance from OEMs to obtain testing materials

Rotorcraft Metal Alloys Listed By OEMs That Lack Sufficient Crack Growth Properties

Aluminum Alloys

2024-T42 Sht
7050-T7451 .25”Plt
7050-T7452 Forging
7140-T7451 Thk Plt
7150-T7751 Plt
7085-T7452 Forging
7085-T7651 Plt

Magnesium Casting

AZ91E
WE43A-T6
EV31-T6
ZE41A

Steel Alloys

Cronidur 30 Forging
4340 (150-175 ksi) Forging
AerMet 100
PH13-8Mo, H1100 Forging
Pyrowear 53 Forging, Carbonize
9310 (150-175 ksi), Forging, EB Welded

Titanium

Ti-4.5Al-3V-2Fe-2Mo
Ti-6Al-4V Beta Annealed Forging
Ti-10V-2Fe-3Al Forging

Task 4 – Development of Crack Growth Properties Lacking For Rotorcraft Metal Alloys

Progress:

(1) Alloys earlier tested by JSC (Supplied by Sikorsky):

Ti-6Al-4V STA & STOA Forging

9310 Steel Forging

7075-T73 & 7076-T6 Forging

7050-T7451 6” Thk Plate

(2) Task 4 testing presently in progress:

7085-T7452 Forging (Material from Alcoa)

(3) Task 4 remaining tests & schedules:

- Primarily depends on receiving test materials from OEMs

Major Purchases and Funding Sources

- **<u>NASA (Late FY06):</u>**
  - Two 10kip fatigue systems ($140K)
  - New friction grips on 55kip system ($21K)
  - 4 Crack measuring microscopes ($23K)
- **<u>NASA (FY07 Plans):</u>**
  - 2nd 55kip fatigue system ($112K)
  - Hydraulic manifold modifications ($69K)
  - One additional test technician ($65K)
- **<u>NASA (FY08 Plans):</u>**
  - New 90 GPM Hydraulic Pump
  - High speed 5 kip fatigue system ($70K)

- **<u>FAA Tasks (FY07):</u>**
  - Automated 3D CNC milling machine ($42K)
  - Automated 3D surface grinder (27K)
  - 4 Crack measuring microscopes ($23K)
  - 2 PD500 Potential Drop systems ($20K)

Summary

- Work started and progress made in Tasks 1 & 4
- NASA JSC has allocated significant FY06 & FY07 funding for additional testing equipment and contractor support that is needed.
- Some FAA funding used to purchase automated machining equipment to reduce current costs of fabricating specimens.
- Planned funding for project is satisfactory and current expenditure rate is as scheduled.